Development of a Low Temperature Geothermal Organic Rankine Cycle Standard

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ABSTRACT

Low temperature geothermal is an abundant resource in New Zealand with over 260 sites with a resource temperature of 150°C and lower. The Organic Rankine Cycle is the standard process for low temperature energy conversion. Power plant prospecting, design, and, development is normally carried out by established companies. New Zealand is lacking experience in the design and manufacture of low temperature geothermal ORC plants. Experience can be gained through a thematic analysis of both successful and unsuccessful developments. A thematic analysis is a qualitative investigation that examines patterns and themes in data.

This paper looks at one case study of a low temperature geothermal Organic Rankine Cycle and organizes the data into four key areas: prospecting, concept plant feasibility, detailed design, and, construction and results. Future research requires more data to validate these patterns. The outcome of this analysis will be the foundation for a low temperature geothermal design standard for the Above Ground Geothermal Allied Technologies research co-operative (AGGAT).

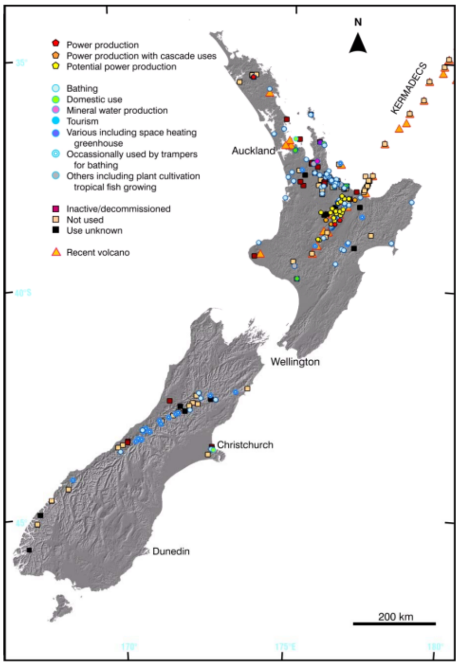

Figure 1 Low Temperature Geothermal sites across New Zealand, Image from GNS [1]

1. INTRODUCTION

1.1 Low Temperature Geothermal

Low temperature geothermal (LTG) heat is a common resource in New Zealand. GNS defines LTG or Low Enthalpy Geothermal to be a geothermal resource at temperatures between 0-150°C[2]. LTG sources can be found at a number of sites around New Zealand most of which are in the Taupo Volcanic Zone.

LTG heat can come from a number of sources, figure 1 shows geothermal sites across New Zealand. LTG heat can be found in naturally occurring hot springs, abandoned hydrocarbon wells, unsuitable geothermal wells, and unused brine.

1.2 Technology

The most used system of converting geothermal heat into electricity is an Organic Rankine Cycle (ORC). An ORC uses an organic fluid in a closed loop Rankine Cycle. The four main components of the ORC are the feed pump, vaporizer, expander, and condenser. New Zealand currently uses a number of ORCs for generating electricity from geothermal heat. Typically ORCs utilize moderate temperature geothermal fluids opposed to LTG fluid because of economic reasons. The usual manufactures of ORCs do not focus on LTG heat because the plant output typically is much smaller than moderate to high temperature geothermal power plants. The Chena geothermal project is an example of a successful LTG electrical generation. Chena shows that it is possible to design an ORC for a low temperature resource without commissioning the usual large geothermal ORC design companies. The Chena geothermal power plant produces 400 kWe of electricity and can produce it at 5 cents per kWh [3]

1.3 ORC Design Standard

There is currently no design standard for ORCs. A design standard could encourage more power companies to pursue LTG heat as a power generation resource. 'A standard is distilled wisdom of people with expertise in the subject matter' (BSI,2013) [4]. Standards consistently provide requirements, specifications, and guidelines for product design and ensure the product is fit for purpose[5].

The Above Ground Geothermal Allied Technologies (AGGAT) standard is being developed as an industry tool for ORC design. The final product is intended to be an accepted standard that can be easily used by industry. The current status of the standard is to develop the framework and key steps from which experienced members of industry can contribute. Figure 2 shows the proposed four main steps for the standard.

Figure 2 The main steps in the proposed standard

1.3.1 Thematic Analysis

The framework of the standard will be developed by investigating a number of different ORC projects and extracting the main aspects of each development. A thematic analysis suits this process because it is a qualitative data analysis for identifying themes and patterns within the data: this is done by coding and classifying data into similar themes. Figure 3 shows that sources that can be used for a thematic analysis of LTG ORC design.

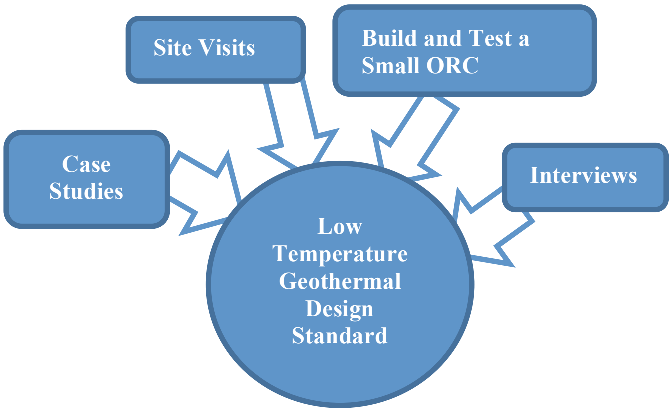

Figure 3 Sources of possible information for the thematic analysis to develop a Low temperature geothermal design standard.

2. STANDARD

2.1 Prospect

The proposed standard identifies four key steps in the development of an ORC. The first step is the prospecting stage; this section is to assess the heat resource for electricity generation with an ORC. Figure 4 shows important internal key aspects of the prospect stage. In the case for a LTG resource the prospect stage assumes that the resource is already understood and no more reservoir investigation is expected. The main goal of this step is to check whether the geothermal resource is suitable for an ORC. The owner conference will also identify if electrical generation is the best option and whether it is connected to the grid or used directly with nearby industry. In some cases direct use of the geothermal heat may be the better option. The maximum allowable temperature drop of the geothermal fluid is an important design parameter for ORC design. A large temperature decrease in geothermal fluid can contribute to significant scaling and reduced efficiency in the heat exchanges.

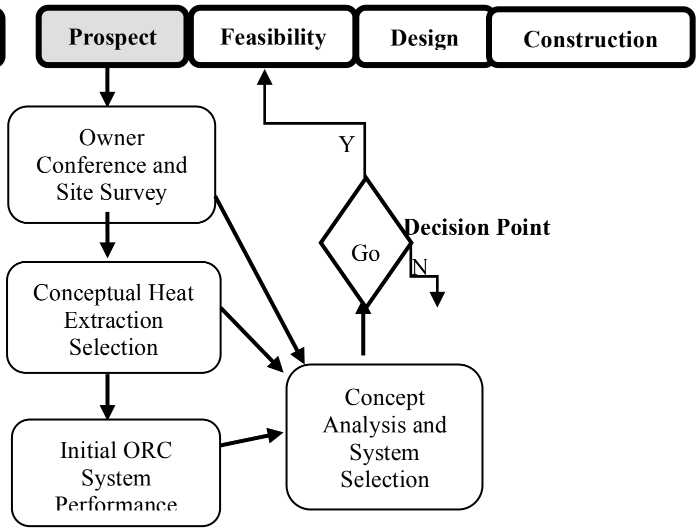

Figure 4 The prospecting stage steps in the current version of the ORC standard

The next step is a conceptual heat extraction selection which will be used for a rough estimation of the size of the ORC and performance. The properties of the geothermal fluid determine what type of heat exchanger is selected. The operating conditions of the working fluid are given consideration however the geothermal fluid is typically the deciding fluid. Once a conceptual heat exchanger is chosen a basic thermal analysis can estimate the footprint of the ORC as the heat exchangers are the largest part.

The final step in the prospect stage is estimating the proposed ORC performance, such as the power output and efficiency. Initial cost estimates and payback period can be made after this step and this can lead to further analysis with the next step or the decision to abandon the project. The first step should require a small investment to reduce the risk if the project is abandoned at this point.

2.2 Feasibility

The purpose of the feasibility section is to further develop the initial model from the prospect step to determine if the project can be economically feasible. The selection of working fluid is the first step in a more detailed thermal analysis of the ORC. The working fluid must be able to operate between the system constraints set by the geothermal source and the environment. The selection of the working fluid is critical because it determines the other components in the system.

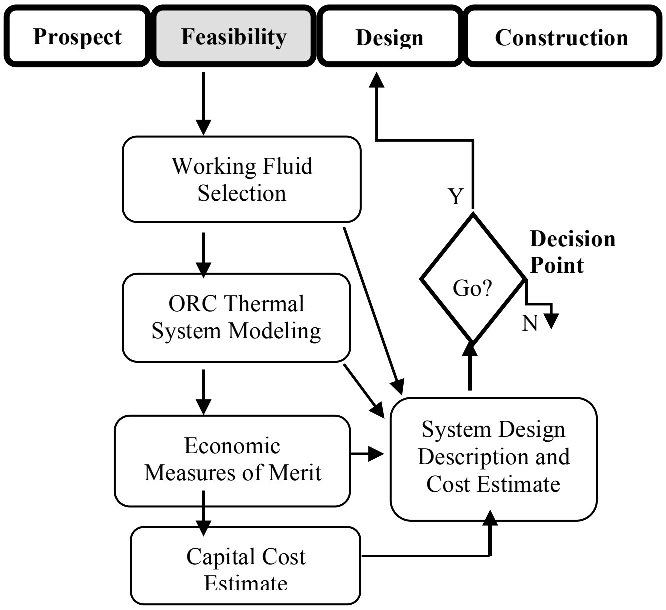

Figure 5 Flow diagram outlining the feasibility stage of the current version of the ORC standard

The thermal model from the prospecting step is reviewed and the ORC and its all components are modeled in more detail. At this step the engineer can investigate whether other components such as regenerators and preheaters are required. A regenerator is commonly used when there is a lower temperature limit on the geothermal fluid. A regenerator does not increase the power output of the system but does however increase capital cost. Pinch point analysis for the heat exchangers is used to validate the model and also determine the optimum design. The thermal model will also determine required flow rates of working fluid, geothermal fluid, and cooling fluid for the optimum design. ORC outputs from this analysis also include any parasitic losses on the system and pressure losses through the heat exchangers.

The detailed thermal model will help determine the economics of the system. An economic analysis of the system can determine the unit savings of energy over the proposed lifetime of the ORC. The economics also determine the payback period and the net present value of the entire system. Any government incentives are also investigated at this point to help reduce the capital cost of the system.

The final step of the feasibility analysis is a revised capital cost estimate. After the thermal modeling there is a better understanding of the components required for the ORC.

2.3 Design

This section is used to specify a detailed design of the proposed ORC. The detailed design will produce specifications for fabrication or selection of appropriate components. The information from the detailed design would be enough to give a highly accurate capital cost estimate.

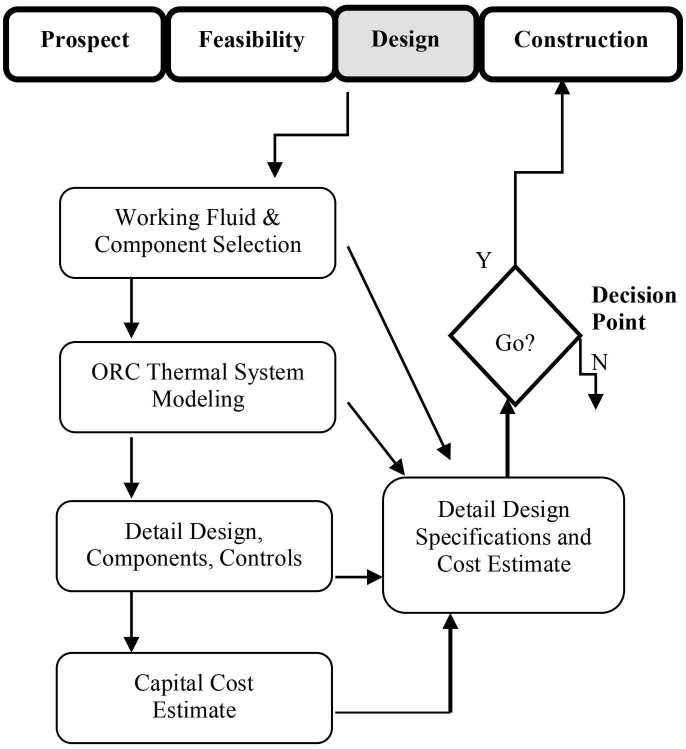

Figure 6 Design process stage in the current version of the design standard

The optimum working fluid was determined in the feasibility study. Now, the working can be chosen given the added consideration of availability and affordability. The component selection and design also relies on the working fluid selected. Throughout the design it should be ensured that the thermal system model is updated with any new design decisions, especially if the optimum working fluid is not available as this can have a significant effect on the model.

A detailed design of the heat exchangers will provide information for the project engineers to decide on whether to purchase the two heat exchangers or manufacture the components themselves. A critical component to the success of the ORC is the expander which is coupled to the generator. Typically, turbines are used on large ORCs to produce the most work from the cycle; however, it is possible to design small ORCs using alternative expanders, such as, a scroll expander [6] or a screw expander, which is used by the ElectraTherm Green Machine [7]. Once the detailed design is complete the capital cost estimate will be much more accurate and can be used to decide whether to continue onto the construction phase.

2.4 Construction

The construction section is to develop a detailed plan for construction; this stage is the final step in the ORC design guide and begins once the full detail design is complete and components can be sourced for the ORC. In this phase, the ORC parts are all ordered and connected. The piping and required instrumentation for the control system should also be installed. Once the ORC is completed the system should be tested and monitored to determine if it is running as expected. Once it is clear that the ORC operates at steady state it can be commissioned and operation can begin.

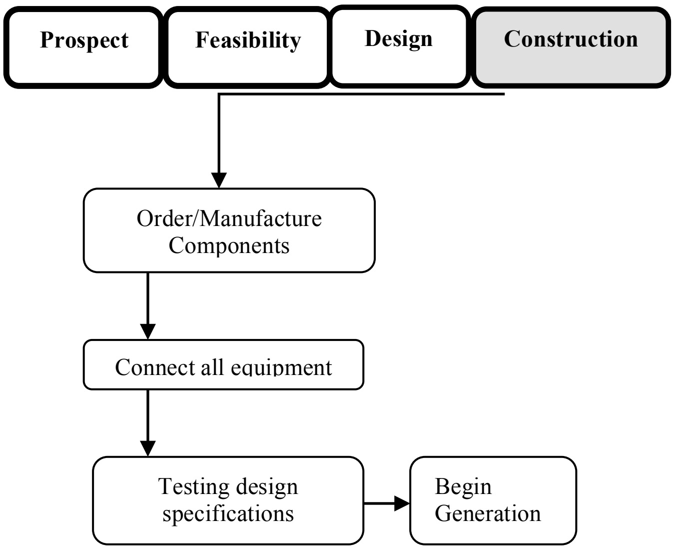

Figure 7 The basic construction process from the current version of the standard for an ORC system

3. CHENA ALASKA

The Chena resort is a remote geothermal site in the middle of Alaska that uses the geothermal heat for electricity and heating for the resort.

3.1 Motivation

Originally the Chena resort used a diesel generator for electrical generation. The average cost to run diesel generator for the 180-380kW load at Chena was $1000/day in 2004 and close to 500,000 per year. The vision of Chena springs was to become a self-sustaining community in terms of energy, food, heating and fuel.

Electricity at Chena was costing 30¢/kW. In 2004 Chena began their energy independence plan to increase the use of locally available resources, including geothermal. Geothermal heat was used to heat 44 buildings and the geothermal resource was also used for an absorption chilling to cool the Aurora Ice Museum and there was also interest in using the geothermal resource for power generation. Electricity production from geothermal heat could reduce the cost of electricity in Chena to 5¢/kW.

3.3 Resources

The geothermal resource was explored in the late 70's and early 80's; however, the results discounted the site for power generation with the technology of the time. The Chena geothermal project decided to take a two-tiered approach for electrical generation. Two projects ran simultaneously; the first to install a small geothermal plant designed from the existing proven resource and the second a more extensive exploration of the deeper geothermal resource and its potential for long term sustainability.

The Chena hot springs are one of around 30 low to moderate temperature geothermal sites in Alaska. The proven resource is geothermal brine with a temperature around 74°C, which makes this the lowest temperature geothermal resource for electricity generation in the world. Another important resource consideration is the geothermal brine chemistry as this affects the heat exchanger design. The geothermal brine was quite dilute with a dissolved content of only 300 to 388 mg/l and a pH near 9. The geothermal water was also labeled drinkable [3].

One production well is used to supply the geothermal fluid for the Chena power plant. The well is 217 meters deep a submersible pump was installed in the well to achieve the desired flow rates for the power station.

A unique aspect of the Chena geothermal site is the unconstrained supply of cold water at 4.4°C. The cold water can be used as a heat sink in the ORC to achieve a greater temperature difference in the cycle and subsequently produce more work.

3.4 ORC Design

3.4.1 Companies

It was difficult to find geothermal manufactures willing to work on a small generation project. Ormat and Barber-Nichols both provided initial project quotes. Barber-Nichols was selected to provide a 400 kW power plant for Chena. United Technologies Center (UTC) approached Chena and offered to install a PureCycle 200®, which is an ORC design to operate on waste gas and modify it to work with geothermal fluid. UTC was eventually chosen as the manufacturer as it could help further the geothermal field and also Barber-Nichols had not manufactured a geothermal plant since the 80's.

3.4.1 PureCycle 200® Design Changes

The main aspect that made the PureCycle affordable was using the single-stage centrifugal compressor from Carrier chillers, which is a mass produced refrigeration system. The compressor was reversed and used as a single stage radial expander. There were a number of changes made to the waste heat ORC. R245fa was the designed working fluid for the PureCycle; however, at Chena the working fluid was changed to R134a because it was a better match for LTG application. R134a also reduced the cost of the project because it is a cheaper fluid and there is more HVAC equipment compatible with R134a. The working conditions of the ORC are shown below and figure 8 is the T-S diagram of that designed system[8].

Water Design Points

Heat source: Tin = 73 °C Tout = 57 °C Flow rate: 33.4 L/s
Heat sink: Tin = 4.4 °C Tout = 9.4 °C Flow rate: 101.8 L/s

Refrigerant Design Points

Mass flow rate: 12.18kg/s
Evaporator/turbine inlet pressure: 16 Bar
Condenser/turbine exit pressure: 4.4 Bar
Turbine gross power: 250 kW
Pump power: 40 kW
System output power (net): 210 kW

Thermal efficiency: 8.2 %

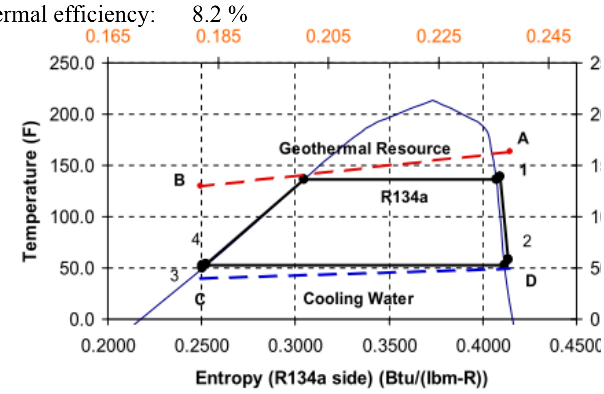

Figure 7 T-S diagram of the Chena geothermal project, Image from Chena Power [3]

The main components that changed in ORC were the heat exchangers: originally they were designed for gas to liquid heat transfer not liquid to liquid. The PureCycle ORC used a fin and tube evaporator for waste heat applications to facilitate the heat transfer between waste exhaust gas and the working fluid. The original condenser design was a fin and tube fan bank.

The evaporator and condenser designed for Chena were once again based on equipment from Carrier refrigeration. Shell and tube heat exchangers were designed for the evaporator and condenser. The evaporator designed for Chena was an integrated preheater and evaporator to reduce components, complexity, and costs. A partition was designed to separate the preheater and evaporator and a distributor nozzle guided the working fluid into the evaporator from the baffled preheater to produce the most heat transfer. The chemistry of the brine did not constrain the material selection process. The final evaporator design specs are listed below[3].

- 2-pass on geothermal resource side,
  - including 1-pass in boiler region, 260 tubes
  - 1 pass in preheater region, 90 tubes
  - ¾" OD, 0.035" tube thickness, Cupro-Nickel 90-10 TurboChill
- 32" OD shell, 10" flanges

The turbo generator for this system was a single hermetically sealed unit. A sealed system reduced maintenance and also shaft leakage common with tradition geothermal turbines. The turbine was only slightly modified from its original purpose as a compressor and so could be manufactured to the same quality as the compressors for commercial chillers. UTC tested the design at their research center for more than 1000 hours before sending it to Chena for LTG electricity generation.

Two 200 kWe ORCs were installed at Chena. The first ORC used the designed water cooled system. The second ORC installed was designed to use either cooling water or an air cooled condenser. The fan bank required 24kW to run opposed to the cooling water which was siphoned out of the nearby; however, the air cooled condenser allowed for a larger temperature difference in the winter months due to the ambient air temperature below -40°C, which produced a maximum net power output of 220 kW[9].

The geothermal generators required a stable grid input during startup. The solution was a 3MW UPS system with a AC/DC inverter to provide the stable input for the generator, which allows the Chena power plant independently from the grid[9].

The PureCycle had a control system installed for its original purpose and this was modified for remote control and monitoring for the Chena installation. A data collection and monitoring system using Labview was installed in the system once it was setup so that UTC engineers and Chena power could monitor the power plant either onsite or remotely.

The owners of Chena recognized the importance of reinjection for the success of any large geothermal project [3]. Two reinjection wells were drilled to reinject 100% of the geothermal fluid. The primary reinjection well is 213m deep and situated far enough away from the main production well to not alter the reservoir.

3.6 Results

The first ORC was installed in August 2006 and the second ORC came in December. The second ORC was designed to also run with an air cooled condenser and ran continuously once installed. The first ORC, which was designed for water cooling, encountered issues with cold water supply in late winter early spring which caused it to shut down. A second air cooled condenser was installed so that both ORCs can either use the cooling water or the air cooled condenser. The plant currently operates to use the water coolers in summer and the air coolers in winter

The project was completed on schedule and with a total cost of $2,007,770 ($5000/kWe) which was only over 5% of the original budget. The projected was partly funded through a grant from the Alaska Energy Authority and a project loan through the Alaska Industrial Development and Export Authority; however, 55% of the project funding came directly from Chena Hot Springs.

A report for the Geothermal Resource Council in 2007 stated that the Chena power plant had been operating with 95% reliability and generated 400MWh[10]. The cost of power was successfully reduced to 5¢/kWh and in 2007 saved an estimated $500,000 on diesel fuel; therefore, the project had a four year payback period on the savings from diesel fuel[11].

The success of the Chena power plant indicates that LTG is a competitive power generation for remote power sites that use diesel generators as their electricity demands. The Chena project also investigated the deeper geothermal resource with hopes that it could one day operate a 10MW power plant that would justify a transmission line to the closest town.

4. CHENA AND STANDARD COMPARISON

Chena is the first LTG case study reviewed and compared to the proposed standard to ORC design.

4.1 Prospect

The first step in the Chena project was a prospecting stage. The resource for Chena was already understood from previous investigations. The site and owners conference is unimportant because the owners of the geothermal site in this case were the ones interested in developing the geothermal resource for electricity generation.

4.2 Feasibility

Once a design company had been selected to design the ORC there are steps that can be connected to the feasibility step of the standard. The most obvious comparison is the working fluid selection. The original PureCycle used R245fa but once the new LTG heat source was understood R134a was chosen because it would yield better results at the lower temperatures. The thermo system was changed with a new working fluid selected. UTC focused on reaching their goal of a low cost ORC for LTG fluid to expand their product range. They focused on utilizing mass produced refrigeration equipment to reduce the capital cost and cost per kilowatt. It was clearly early on that geothermal power at Chena would have a quick payback period because of the high diesel costs, which can be seen as economics in the feasibility section of the standard.

4.3 Design

The design process in the Chena project closely resembles the standards recommended approach. R134a was selected as the working fluid in the ORC and the main components had to be designed and selected for the final product. The expander was the first choice because it was already used in the current setup of the PureCycle. However, the heat exchangers had to be modified to work with the geothermal fluid. The original heat exchangers were not designed for liquid to liquid heat transfer and so UTC developed two new heat exchangers that used a shell and tube design to utilize the liquid resources. Thermal modeling, however, did show that an air cooled condenser in the winter month would yield more net electricity generation. This process once again matched the recommendations in the current standard. The components selection and thermal modeling confirm the detailed design for the project.

4.4 Construction

The whole plant was constructed at UTC and tested to ensure it would run as expected, after testing all equipment was inspected for any damage. The control system was tested at Chena to makes sure it could operate without input from UTC. The second ORC installed at Chena was completed hooked up by Chena employees; UTC employees were there for a short period to setup the control system of the ORC. The construction stage has similar points to the current standard because it was used to test whether the plant was running to the design specifications.

5. CONCLUSION

The results from the first case study shows a correlation between the design processes Chena used for the LTG power plant and the proposed standard process. More case studies still need to be analysed and interviews with engineers on LTG ORC design projects can also help develop standard. Regular communication with industry is an important aspect for the standard because experienced members of industry with expertise with ORCs will understand the important features and what to focus on with the final standard.

REFERENCE

1. Climo, M. and B. Carey, *Low Temperature Geothermal Energy Roadmap: Fostering increased use of New Zealands abudant geothermal resoucres*, in *GNS Science Report*2011, GNS: Taupo.
2. Gazo, F. and L. Lind, *Low Enthalpy Geothermal Energy - Technology Review*, 2010.
3. Chena Power, L., *400kW Geothermal Power Plant at Chena Hot Springs, Alaska.* Final Report prepared for Alaska Energy Authority, 2007.
4. Institution, B.S. *What is a Standard*. 2013

   [cited 2013 23/07/2013]; Available from: http://www.bsigroup.com/en-GB/standards/Information-about-standards/what-is-a-standard/.
5. ISO. *Stages of the development of International Standards*. 2013; Available from: http://www.iso.org/iso/home/standards_development/resources-for-technical-work/stages_of_the_development_of_international_standards.htm.
6. Lemort, V., et al., *Testing and modeling a scroll expander integrated into an Organic Rankine Cycle.* Applied Thermal Engineering, 2009. **29**(14–15): p. 3094-3102.
7. ElectraTherm. *ElectraTherm's Waste Heat to Power Generation System*. 2012.
8. Aneke, M., B. Agnew, and C. Underwood, *Performance analysis of the Chena binary geothermal power plant.* Applied Thermal Engineering, 2011. **31**(10): p. 1825-1832.
9. Holdmann, G. and K. List, *The Chena Hot Springs 400kW geothermal power plant: experience gained during the first year of operation.* Chena Geothermal Power Plant Report, Chena Power Plant, Alaska, 2007: p. 1-9.
10. Benoit, D., G. Holdmann, and D. Blackwell. *Low Cost Exploration, Testing, and Development of the Chena Geothermal Resource*. in *Geothermal Resource Council Annual Meeting, published in proceedings. 9 pages*. 2007.
11. Holdmann, G. *The Chena Hot Springs 400 kW Geothermal Power Plant*. in *Energy Efficiency and Renewable Energy*. 2007. USA.